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High performance corrugated horn antennas for CosmoGal satellite

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Abstract

This paper presents the design methodology for the creation of corrugated horn antennas for the CosmoGal satellite. The mission will collect the radiation of the cosmic microwave background, by a radiometer in three different radio astronomy frequency bands (10.6-10.7GHz; 15.35-15.4GHz; 23.6-24GHz). It is discussed the design study of several types of horns, simulated on the CST software. The best result points to a choked Gaussian corrugated horn antenna, with directivity of 23dBi, side lobes below -35dB and cross polarization better than -45dB.

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Keywords: Corrugated Horn Antennas, Choked Antenna; Gaussian profile horns; CMB; Satellite;

1. Introduction

The characterization of emissions from our Galaxy in the microwave band (1 GHz - 30 GHz) is one of the most important issues of the next decade, from the observational cosmology point of view. The satellite mission CosmoGal aims to study the emissions from the Galaxy in 3 different frequency bands, being these [10.6-10.7] GHz, [15.35-15.4] GHz and [23.6-24] GHz. CosmoGal will use a radiometer as a detector, allowing for the reading of polarized component of the incoming radiation.

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The most suitable horn antenna profile for this purpose is the corrugated profile, which allows for the production of hybrid modes at aperture with high efficiency. This family of horn antennas is also known as Gaussian profiled horns, because of their ability to produce almost perfect Gaussian beams through the use of HE_{11} propagation mode.

The intent of this paper is to study, with CST® software [1], different types of horns to present an optimized choice to operate at the above mentioned frequency bands. These 3 horns – one for each band – should have a low mass and must be small in total length, with the following desired characteristics: side lobe level lower than 35dB, cross polarization bellow to -30dB, return loss bellow -30dB and an edge-taper less than 20dB@20º.

2. Corrugated Horns Theory

2.1. Principles of operation of corrugated horns

The principle of operation of corrugated horn antennas can be explained by the influence of the corrugated walls and how they affect the distribution of the electromagnetic field on the inside [2]. Fig. 1 represents the inside of a corrugated waveguide where R is the radius, d represents the depth, W is the corrugations width and p is the corrugation period.

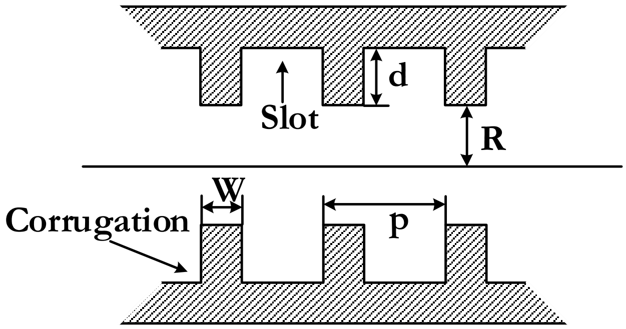

Fig. 1. Corrugated wall.

As it will be shown below, corrugations have the ability to modify the field that travels through the waveguide, resulting in a radiated beam that exhibits axial symmetry, low side lobe level and low cross polarization [3]. To achieve this, the field distribution needs to be approximately linear at the antenna aperture [3]. To accomplish the necessary nearly linear field, it is necessary to use corrugated horns – known, also, as hybrid horns.

Known as such due to their ability to propagate hybrid modes [4]. These modes, like HE_{11}, produced by corrugated circular waveguides, have nearly linear field lines at the antenna aperture, making them perfect to be used in high performance application antennas, as shown in Fig. 2.

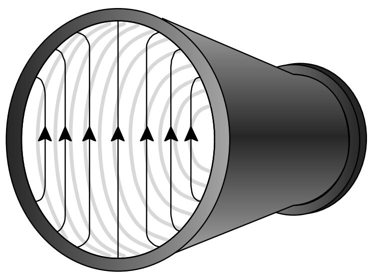

Fig. 2. Electric field in HE_{11} mode of a corrugated horn antenna at aperture.

2.2. Hybrid Modes

Hybrid modes are composed by a mixture of transverse-electric and transverse-magnetic modes along the corrugated waveguide. Despite the fact that corrugated horns can be analysed using the TE and TM modes, it is more useful to analyze them according to the hybrid HE and EH modes. As demonstrated by different authors [2] [5], the optimal way to achieve the minimum levels of cross polarization and maximum directivity is by exciting HE_{11} mode, which is obtained when the balanced hybrid condition is achieved – theoretical condition in which the cross polarization is zero [5] – as can be seen in Fig. 3 (a).

In the design of corrugated horns antennas, one of the main goals is to achieve, at the aperture of antenna, the HE_{11} mode. This mode, which is composed by a mixture of approximately 85% of TE_{11} mode and 15% of TM_{11} mode [3], is optimal for the most demanding applications due to its good radiation characteristics, since the directivity will be maximized owing to a Gaussian power distribution, as represented at Fig. 3 (b).

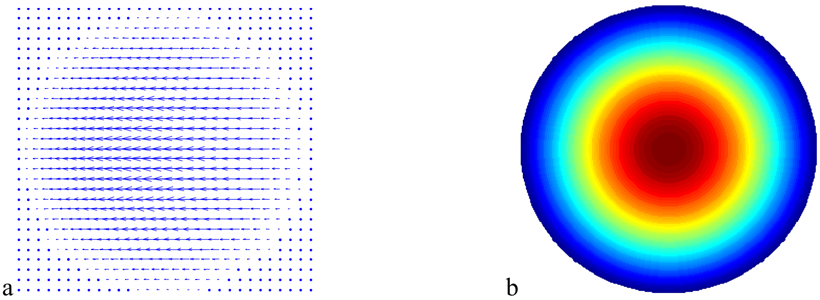

Fig. 3. Electric field of HE11 mode; (a) polarization component; (b) power distribution

The efficiency is a way of measuring the capability of producing beams with the same format of FGM (Fundamental Gaussian Mode) represented by Ψ_0^0. In other words, it is the ability of a guided mode to excite the desired free space mode. The FGM, which is a solution of the free space wave equation, is free from cross-polarization and side lobes, which makes it the ideal free space mode to propagate the waves created at the horn aperture [5].

The similarities between the wave excited by HE_{11} mode and the FGM are analyzed by [5]. The author shows that, for the relationship $R/\omega_0 = 1.554$ between the entry radius of the horn (R) and the initial beam width (ω_0), it is possible to obtain a wave excited by HE_{11} mode with identical properties to the ideal free space wave

3. Analysis and Optimization

3.1. Design Strategy

In this study, CST® [1] was used. It is an electromagnetic simulation software that is not specific for corrugated horn antennas, and because of that it has been necessary to come up with a strategy based in empirical data presented by several authors [5] [3] [4]. These data show that radiation features are closely related with some geometrical parts of the horn antennas and that corrugations have a greater influence over the cross-polar component. In order to achieve the desired goals, the design strategy can be divided into two major parts [6]:

In the first stage, used to improve only the co-polar features, several profiles are tested. In this analysis, parameters like the profiles curvature, flare-angle, aperture dimension and total length are varied in order to obtain an optimized beam.

In the second stage, after defining co-polar features, it is possible to change the corrugations dimensions and the type of impedance transformer to improve and optimize the cross-polarization levels and the return loss. This process is only viable because the changes in the corrugations affects, almost only, cross-polar component, keeping unaffected the co-polar component.

3.2. Horn profile analysis

The first stage of the analysis is to choose the horn profile that offers the better co-polar features, bearing always in mind that the total length and the total weight are extremely important. In this analysis five types of corrugated horns were tested, each one of them with a different profile, being them: Potter Horn (or conical), conical horn with addition of a Gaussian profile, double Gaussian profile horn (2 variations) and choked Gaussian horn. It has been made a parametrical study for the abovementioned profiles, presented in detail at [7], that shows a comparison of the radiation characteristics, for directivities between [21.5-22.5] dBi. The results of this study show that:

For the Potter horn, the flare angle must be as small as possible, to minimize the cross-polar levels (bellow 10º). The use of small flare angles leads to a total length above 14λ; this so happens because it is also needed a wide aperture to have good directivity. However, there is a serious disadvantage in this type of profile horn, the side lobe level is limited to -25dB for directivities around 22dBi.

For the conical horn with the addition of a Gaussian profile, it must be used flare angles, in the impedance transformer, below 10º to improve the cross-polar levels, the phase center and the side lobe levels. The disadvantage lies in a reduction of the directivity and in an increase of the total length. The advantage, in comparison with Potter horn, is that, through the addition of an Gaussian profiled section at the end of the horns of $4\lambda - 6\lambda$ to an impedance transformer of 7λ, it makes possible to achieve side lobe levels of -30 dB, for directivities of 22 dBi and edge-taper of -20 dB @ 20º, for a total length of 13λ.

The double profiled horn antenna, that uses a nonlinear profile in both impedance transformer section and radiation section, has the advantage of possess an initial section with a subtle aperture, however shorter than the others. Other advantage in the usage of this initial profile, in comparison with the above mentioned horn antennas, is that this allows the creation of an antenna with side lobe levels of -35 dB, edge-taper of -20 dB @ 20º and a directivity of 21.4 dBi, for a total length of 12λ.

The inverted Gaussian profiled horn, which is a variation of the double profiled horn antenna, differs only from the mathematical expression of the impedance transformer design. This design makes the transition between impedance transformer and radiation sections even more subtle, improving the cross-polar levels, with an directivity of 22 dBi, a side lobe level of -35 dB and maintaining the edge-taper in -20 dB @ 20º. However, this profile has the disadvantage of having a slightly longer size, of 14λ.

The choked Gaussian horn, because of the impedance transformer of the choked type with horizontal corrugations, allows a significant reduction of the total length of the antenna. Unlike the other analyzed profiles, this one has an impedance transformer of just 1.43λ of length, whereas the radiation section has a similar dimension, when compared with the other horn antennas. The total length is the biggest advantage of this kind of profiles, however, their radiation features are not inferiors. For a total length of 7.43λ, this horn antenna shows a directivity of 22.5 dBi, side lobe levels of -35 dB and an edge-tape of -25 dB @ 20º.

Table 1 synthetizes the obtained results, presented in the above mentioned text.

Table 1. Summary of results for different profiles.

	Potter	Conical + Gaussian	Double Gaussian	Inverted Double Gaussian	Choked Gaussian Profile
Length [λ]	16.37	13.08	12.067	14	7.43
Aperture Radius [λ]	2.4	2.85	2.54	3.26	3.61
Directivity [dBi]	22.3	22.34	21.4	21.97	22.97
Side Lobe Levels [dB]	-25	-30	-33	-35	-35
Edge Taper [dB@20º]	-25	-20	-19	-20	-25
Return Losses [dB]	-40	-40	-40	-50	-37
Cross Polarization [dB]	-50	-45	-40	-45	-30
Phase Center (from the aperture) [λ]	2.5	4.66	3.36	2.75	5.2

The dimensions used on profiles with only vertical corrugations are as follows: corrugations period of 0.2λ, slots of 0.0667λ. In the impedance transformer, the first corrugation has a depth of 0.5λ, decreasing linearly until 0.25λ in the last corrugation. This final depth is maintained along the radiation section until the antenna aperture.

In the choked Gaussian horn antenna, an impedance transformer has been used in such a way where the horizontal corrugations have a period of 0.161λ, a slot spacing between corrugations of 0.0643λ and a depth of 0.225λ. In the radiation section, the period between corrugations is 0.23λ, the slot spacing between corrugations is 0.097λ and the corrugations have a depth of 0.2831λ.

From Fig. 4 to Fig. 8, it is presented a comparison of the above mentioned horn antennas, for directivities between [21.5-22.5] dBi. In this comparison it is possible to see the reduced dimensions of the choked Gaussian horn antenna, when compared with the rest of the profiles. Because in this study the most important aspects are the total dimension and the weight of the horn, the choked Gaussian horn antenna was the chosen model for further optimization analyses, in the frequency bands of interest.

The choked Gaussian profile is defined mathematically by (1)

$$R(z) = \begin{cases} \alpha_{IT}.z + R_i & 0 < z < L_{IT} \\ R_{0_{IT}}.\sqrt{1+\left(\dfrac{\lambda.z}{\pi.\alpha_{RadSec}{}^2.R_{0_{IT}}{}^2}\right)^2} & \mathrm{L}_{IT} < z < L \end{cases} \quad (1)$$

where R_i is the waveguide radius, α_{IT} is the flare angle of the impedance transformer, α_{RadSec} is the dimensionless parameter that directly influence the curvature of the radiation section, R_{0IT} is the radius of the impedance transformer aperture, L_{IT} is the length of the impedance transformer and L represents the total length of the antenna.

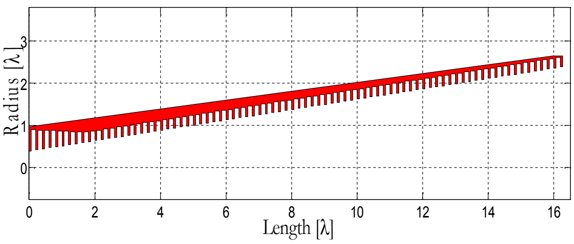

Fig. 4. Dimension of 22 dB conical (Potter) profile.

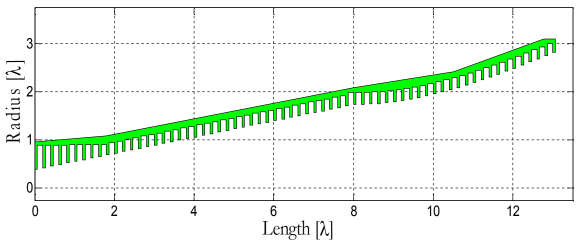

Fig. 5. Dimension of 22 dB conical + Gaussian profile.

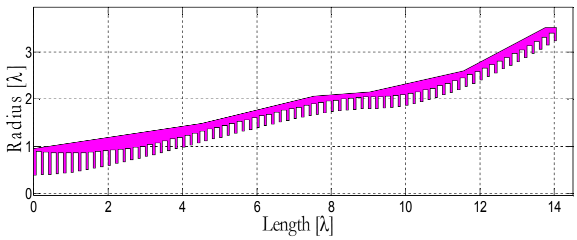

Fig. 6. Dimension of inverted double Gaussian profile.

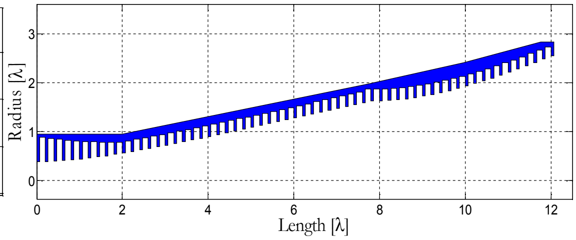

Fig. 7. Dimension of double Gaussian profile.

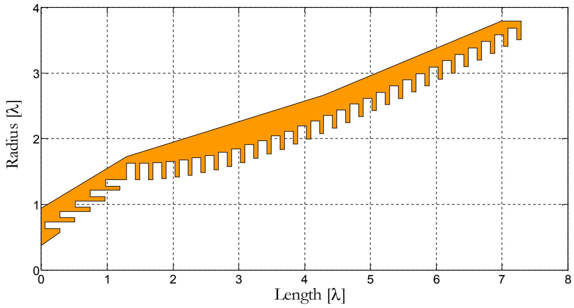

Fig. 8. Dimension of choked Gaussian profile.

3.3. Choked horn antenna with addition of Gaussian profile

As seen before, the corrugations alter, almost only, the cross-polarization component and because of that their dimensions are used for optimization, after the co-polar component has been reached.

The optimizations made show that the corrugations of the impedance transformer must have 5 corrugations wide of constant dimension, with a length of 1.43λ. The corrugations of the radiation section must have a depth of 0.27λ to achieve the finest cross-polarization levels. The optimized choked Gaussian profile and its dimensions are presented in Fig. 9 (a) (b) e (c), for each frequency band of interest.

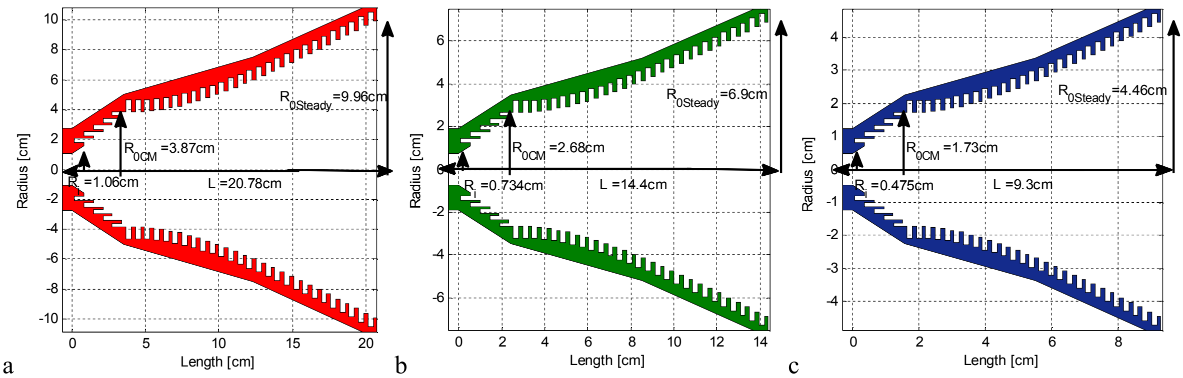

Fig. 9. Choked Gaussian horn dimensions for (a) 10.6-10.7 GHz ; (b) 15.35-15.4 GHz; (c) 23.6-24 GHz.

About the radiation characteristics of the horns, depicted on Fig. 9 , directivities around 23 dBi have been reached and, for the dimensions presented in the previous paragraph, it was possible to achieve return loss[†] levels below -34 dB (see Fig. 10), cross-polarization levels lower to -45 dB, side lobe levels inferior to -37 dB, edge-taper of -25dB @ 20º and optimal axial symmetry for angles under 20º in all frequency bands, as it can be seen in Fig. 11 (a) (b) e (c).

† The impedance reference for the matching levels was the feeding waveguide mode impedance.

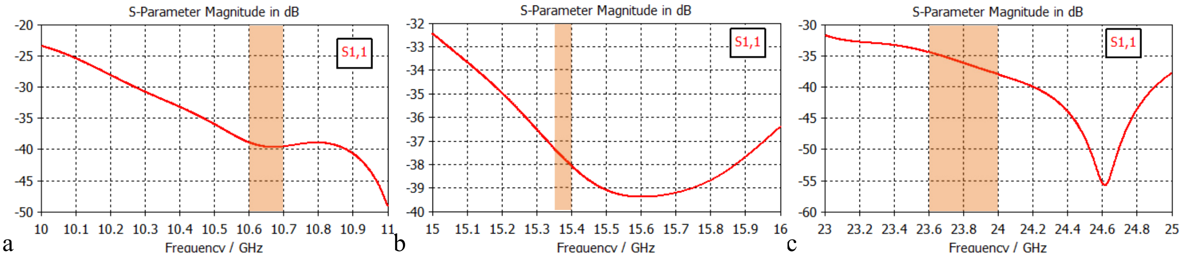

Fig. 10. Choked Gaussian horn return loss for (a) 10.6-10.7 GHz ; (b) 15.35-15.4 GHz; (c) 23.6-24 GHz.

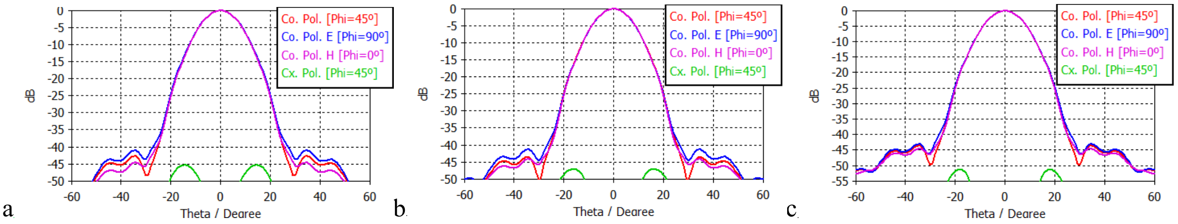

Fig. 11. Radiation Characteristics of Choked Gaussian horn for (a) 10.6-10.7 GHz ; (b) 15.35-15.4 GHz; (c) 23.6-24 GHz.

4. Conclusion

In this paper a solution has been presented for narrowband horn antennas, in order to gather information from the cosmic microwave background. These choked horns are considered high performance because of their ability of produce high quality radiation characteristics and also being small in length. From the five horn antennas considered, the choked Gaussian corrugated horn has proven to be the only type able to produce beams of high quality, with very good axial symmetry, side lobe levels inferior to -37 dB, return loss below -34 dB, cross-polar levels under -45 dB, directivities of 23 dBi, edge-taper of -25 dB @ 20º and, all these features, for an extremely compact horn antenna of 7.43λ total length.

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